論文96-33B-2-23

퍼지PI 제어기를 사용한 스위치드 리럭턴스 전동기의 속도제어

(The Speed Control of the Switched Reluctance Motor using Fuzzy PI Controller)

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요 약

본 논문은 퍼지 PI 제어기를 사용한 스위치드 리럭턴스 전동기의 속도제어에 대하여 다루었다. 퍼지 로직 제어는 알고리즘을 형성하기 위한 정확한 수학적인 모델을 요구하지 않기 때문에 비선형시스템을 제어하는데 적합하다. 퍼지 PI 제어기는 단일칩 마이크로콘트롤러인 MCS80C196KB에 의하여 구현되었고, SRM의 전류(轉流)로직을 위해 EPROM을 사용하였다. 시뮬레이션 및 실험결과에서 퍼지 PI 제어기가 응답시간, 정정시간 및 오버슈트면에서 종래의 PI 제어기에 비하여 우수한 성능을 나타내었고, 특히 시스템의 강인성이 크게 향상되었다.

Abstract

This paper deals with the speed control of the switched reluctance motor using fuzzy PI controller. A fuzzy logic control provides a good approach to nonlinear system because it does not require a detailed mathematical model to formulate the algorithm. The fuzzy PI controller is implemented by MCS80C196KB, a 16 bit one-chip microcontroller, and an EPROM is used for the commutation logic of the SRM. The simulation and experimental results show that the performance of the fuzzy PI controller is superior to that of the conventional PI controller in terms of response time, settling time and overshoot. In particular, the robustness of the system is largely improved.

I. Introduction

In recent years, there is an increasing interest in switched reluctance motors(SRM) which is the simplest of electrical machines. Because of its robustness and high reliability, the SRM is independent of the operating environment and is qualified to run both at very high speed and at low speed[1]-[4].

A PI controller is widely used in SRM drive systems[1][2]. A PI controller adjusts the system control parameters on the basis of the differential equation which represents the plant dynamics. Therefore, it requires a detailed understanding of all the variables in the system.

As the inductance of the SRM is not a constant and varies continuously with the

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接受日字:1995年8月10日, 수정완료일:1996年1月3日

rotor position, it does not have a steady-state equivalent circuit[2]. For this reason, it is difficult to determine the gain of a PI controller. Furthermore we can not obtain the good response for the change in the load torque and the load inertia moment using PI controller.

To overcome the above problems, the fuzzy control based on the fuzzy algorithm advocated by Zadeh[5] is the effective strategy.

In a fuzzy controller, the adjustment of control signals are determined by the fuzzy rule-based expert system, thus it does not require a mathematical model of the system. Hence, it is most applicable to the nonlinear, time-variant system. Recently the fuzzy control is applied to a motor drive system with nonlinearity, parameter variation and load disturbance[6]-[9].

In this paper, the fuzzy PI controller is proposed for the speed control of the SRM.

The fuzzy controlled SRM drive system is studied by simulation and the performance of it is experimented.

The simulation and experimental results show that the performance of the fuzzy PI controller is superior to that of the conventional PI controller. Especially, the robustness of the system over the load disturbance is largely improved. The fuzzy controller is implemented by MCS80C196KB, a 16 bit one-chip microcontroller[10].

II. Fuzzy PI Speed Controller

The fuzzy PI controller which is analytically equivalent to a PI controller is adopted as a speed controller. We used the dual mode fuzzy controller consisting of two control modes: coarse mode and fine mode.

1. Fuzzification.

The fuzzification is a translation from a crisp value to a fuzzy term.

In a fuzzy PI controller, the input variables are the speed error(E) and the change of the speed error during the sampling time(CE), and the output variable is the change of the control input(du). At a sampling point k, the variables E and CE can be expressed as follows:

$$E(k) = \omega^* - \omega(k) \tag{1}$$

$$CE(k) = E(k) - E(k-1) \tag{2}$$

where ω^* and ω are the speed command and the actual speed of the SRM.

These input variables are expressed in terms of linguistic variables using fuzzy subsets. In this paper, we used five fundamental fuzzy linguistic variables: negative big(NB), negative small(NS), zero(ZO), positive small (PS), positive big(PB).

Fig. 1 shows the plot of triangular membership functions for the variables E, CE and du which are expressed in per unit(p.u) quantities. Each variables have been normalized between the -1 and +1 values

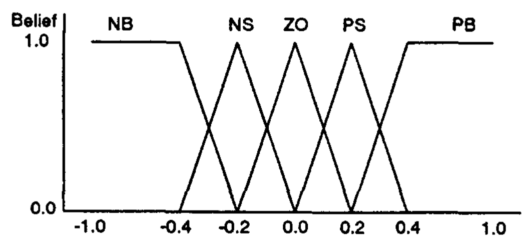


그림 1. 소속 함수
Fig. 1. Membership function.

2. Inference Method

The inference is a induction of the fuzzy output from the fuzzy input.

To obtain good control results, it is necessary to formulate proper control rules.

Table 1 shows the rule table of the fuzzy PI controller where all the entries of the matrix are the fuzzy sets of error, change of error and change of control input of the SRM.

It has 25 rules which are developed by heuristics from the viewpoint of practical system operation.

As an example, if a control rule in Table 1 reads

IF E is PB and CE is PB THEN dU is PB

this implies that "If the present rotor speed is much slower than the speed command and the rotor speed is increasing very fast, then increase the control input largely."
The MAX-MIN composition is chosen as the fuzzy inference method and we can get:

$$du = \bigvee_{\substack{e \in E \\ ce \in CE}} [\, E(e_i) \wedge CE(ce_j) \wedge R(e_i, ce_j, du_k) \,] \quad (3)$$

표 1. 제어 규칙
Table 1. Rule Table.

E \ CE	NB	NS	ZO	PS	PB
NB	NB	NB	NB	NB	NB
NS	NB	NS	NS	ZO	ZO
ZO	NS	NS	ZO	PS	PS
PS	ZO	ZO	PS	PS	PB
PB	PB	PB	PB	PB	PB

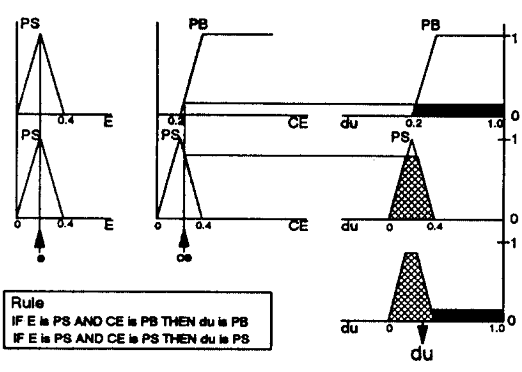


그림 2. MAX-MIN 합성법
Fig. 2. MAX-MIN composition.

3. Defuzzification

The output of the fuzzy PI controller is a fuzzy set of the change of control input. As the plant usually requires crisp values of a control signal, a defuzzification stage is needed.

The defuzzification is translation from fuzzy output back into numerical values for system action.

For defuzzification, the center of gravity (COG) method which determines the crisp controller output as the center of gravity of the final combined fuzzy set is selected.

For a sampled data representation, the center of gravity *du* is computed point-wise by

$$du = \frac{\sum_{j=1}^{n} \mu(u_j) \cdot u_j}{\sum_{j=1}^{n} \mu(u_j)} \quad (4)$$

Fig. 3 shows the configuration of the fuzzy PI controller which consists of input-output scaling, fuzzification, fuzzy decision and defuzzification. The scale factors *SE*, *SCE* and *SdU* change the inputs and output of the controller proportionally. The change of control *du* is inferred from the two state variables *E* and *CE*, where each is obtained from dividing the actual signal by the respective scale factor. The output signals are defuzzified and multiplied by the scale factor in order to construct the actual change of control signal *dU*.

The output scale factor is selected differently according to the control mode which is determined by the magnitude of the speed error.

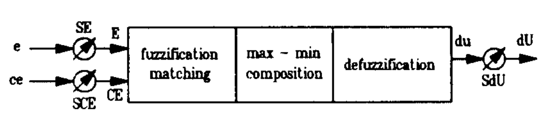


그림 3. 퍼지 PI 제어기의 구조
Fig. 3. Structure of the fuzzy PI controller.

Fig. 4 shows the block diagram of the complete SRM drive system where the fuzzy PI controller is indicated. The circuit enclosed with the dashed line is virtually constructed with a one-chip microcontroller MCS80C196 KB. The *CE* signal is actively derived as the change signal of *E* between the successive sampling intervals. The *E* and *CE* signals are first fuzzified, then processed through a fuzzy rule base and finally defuzzified to generate the change of control *dU* signal. Finally the *dU* signal is integrated to construct the control signal *U*.

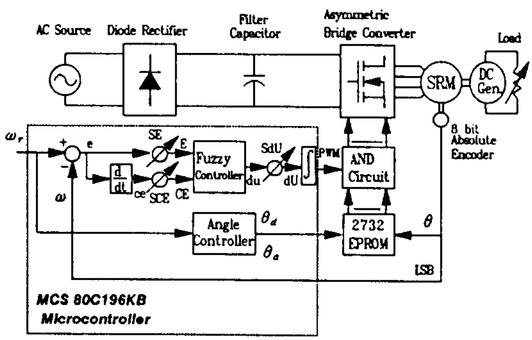
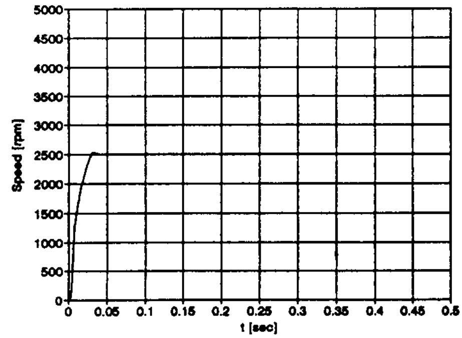


그림 4. 퍼지 PI 제어기를 사용한 SRM 구동시스템의 블록도
Fig. 4. The block diagram of the SRM drive system using fuzzy PI controller.

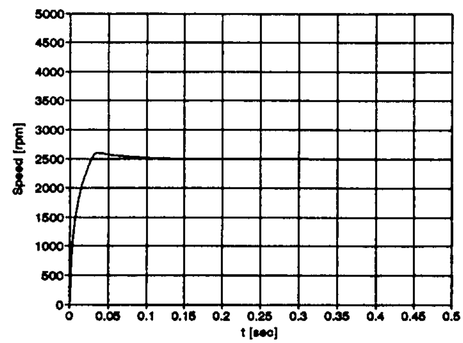
Ⅲ. Simulation Results

Assuming the linear inductance, the simulation of the total system was made using the C language. The change of control input is obtained by the fuzzy inference, and the defuzzification selects the real change of control input using above obtained membership function. The change of error is calculated from the present and past values of the speed error. According to the value of speed error, either the coarse or the fine control mode is automatically selected.

In order to minimize the sampling time, the universe of discourse for *E* and *CE* is quantized into 21 levels and for each combination of quantized input signals, the precalculated change of control signal *dU* is stored in the form of look-up table.



(a)

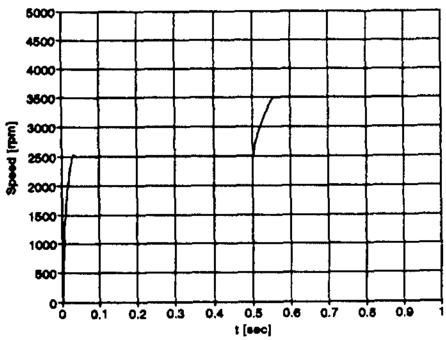


(b)

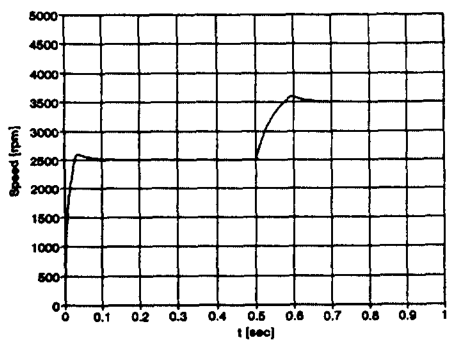
그림 5. 2500rpm의 지령속도에 대한 속도 응답 (T_L=0.21N.m)
(a) 퍼지 PI 제어기를 사용한 경우
(b) PI 제어기를 사용한 경우
Fig. 5. Speed response for the reference speed of 2500rpm.(T_L=0.21N.m)
(a) using fuzzy PI controller
(b) using PI controller

After reading the change of control signal *dU* from the look-up table, it is added to the previous control input signal *U*, the duty cycle of the PWM.

The performance of the proposed system is compared to that of a digital controlled system with a PI controller in Fig. 5~7. Fig. 5 shows the step response for the reference speed of 2500rpm. Fig. 6 shows the step response of the speed reference change from 2500rpm to 3500rpm. Fig. 7 shows the speed response to the load increase at t = 0.5s. As the Fig. 5~7 indicate, the performance of the system with the fuzzy PI controller is much superior to that of the system with the conventional PI controller. From the magnified waveform in figure 7, we can also see the superiority of the fuzzy PI controller in terms of the torque ripple which is one of the most serious demerits in the SRM drive.



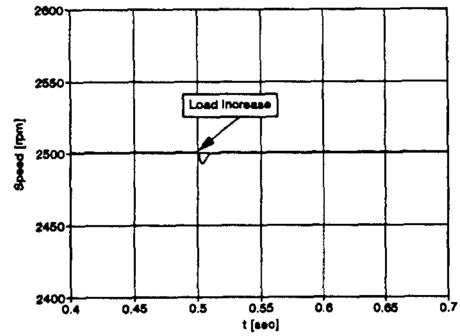
(a)



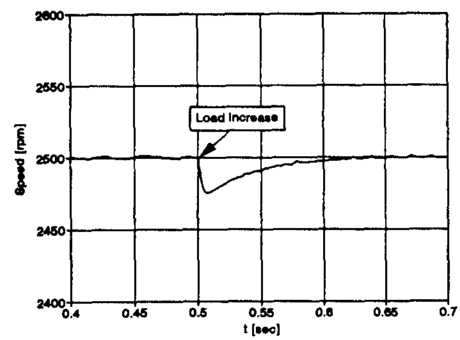
(b)

그림 6. t =0.5초에서 지령속도에 변화를 준 경우의 속도응답(2500rpm→3500rpm, T_L= 0.21N.m)
(a) 퍼지 PI 제어기를 사용한 경우
(b) PI 제어기를 사용한 경우

Fig. 6. Speed response for the reference speed change at t=0.5s.(2500rpm→3500rpm,T_L=0.21N.m)
(a) using fuzzy PI controller
(b) using PI controller



(a)



(b)

그림 7. 부하증가에 대한 속도응답(T_L: 0.21N.m →0.42N.m)
(a) 퍼지 PI 제어기를 사용한 경우
(b) PI 제어기를 사용한 경우

Fig. 7. Speed response for the load increase.(T_L: 0.21N.m→0.42N.m)
(a) using fuzzy PI controller
(b) using PI controller

Ⅳ. Experimental Results

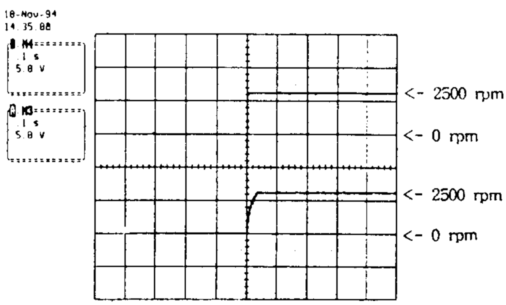
The 8/6 pole SRM drive system with a asymmetric bridge converter was tested in the laboratory to substantiate the simulation results. In this system, an 8 bit absolute encoder is used as a position sensor and an 2732 EPROM is used for the the commutation logic.

At a high speed, it is necessary to control the turn-on timing and turn-off timing so as to obtain enough current for a given load torque. This is usually controlled by two conrol angles: the advance angle and the dwell angle.

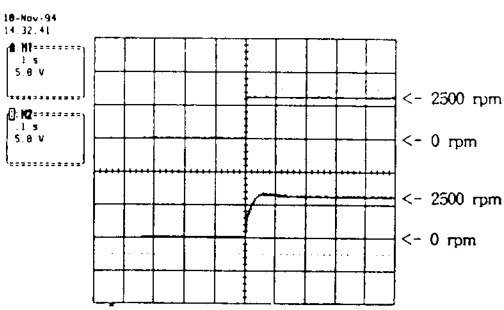
표 2. SRM의 각도제어
Table 2. Angle control of the SRM.

reference speed	advance angle	dwell angle
0 - 500rpm	3°	15°
500 - 1800rpm	6°	15°
1800 - 3600rpm	8°	15°
3600rpm -	11°	18°

Table 2 shows the control angle of the SRM. These advance angle and dwell angle for the reference speed are determined by experiments.



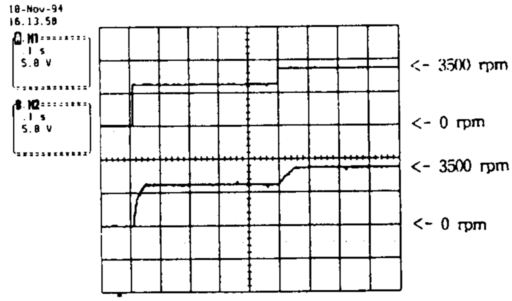
(a)



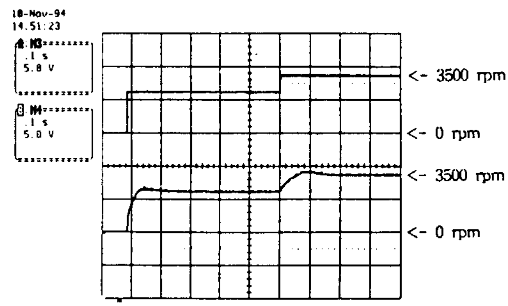
(b)

그림 8. 2500rpm의 지령속도에 대한 속도 응답 (T_L=0.21N.m)
(a) 퍼지 PI 제어기를 사용한 경우
(b) PI 제어기를 사용한 경우

Fig. 8. Speed response for the reference speed of 2500rpm.(T_L=0.21N.m)
(a) using fuzzy PI controller
(b) using PI controller



(a)



(b)

그림 9. t =0.5초에서 지령속도에 변화를 준 경우의 속도응답(2500rpm→3500rpm, T_L=0.21N.m)
(a) 퍼지 PI 제어기를 사용한 경우
(b) PI 제어기를 사용한 경우

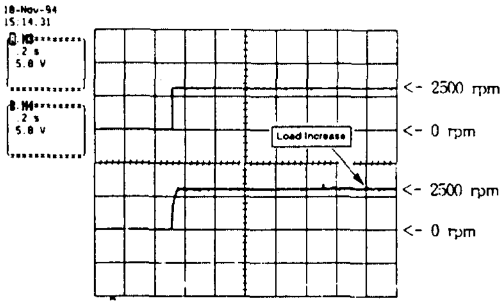
Fig. 9. Speed response for the reference speed change at t=0.5s.(2500rpm→3500rpm,T_L =0.21N.m)
(a) using fuzzy PI controller
(b) using PI controller

Fig. 8~10 show the experimental results of the SRM drive system with the fuzzy PI controller and the conventional PI controller under the same conditions as in simulation. These experimental results confirm the simulation results of the superiority and robustness of a fuzzy PI controller.

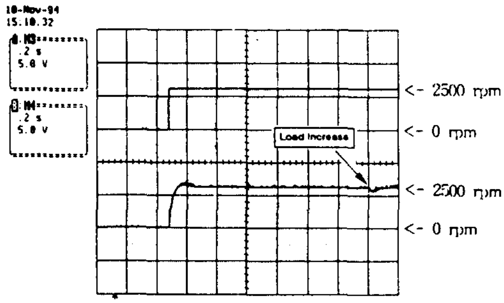
V. Conclusion

This paper deals with the speed control of the SRM using fuzzy PI controller.

Through simulation and experiments, it has been shown that fuzzy PI controller offers the following advantages:



(a)



(b)

그림 10. 부하증가에 대한 속도응답(T_L: 0.21N.m→0.42N.m)
(a) 퍼지 PI 제어기를 사용한 경우
(b) PI 제어기를 사용한 경우

Fig. 10. Speed response for the load increase.(T_L: 0.21N.m→0.42N.m)
(a) using fuzzy PI controller
(b) using PI controller

(1) It is confirmed that the fuzzy PI controller can effectively control the SRM with nonlinear characteristics and reduce the torque ripple of the SRM.

(2) Both the response time and the settling time of the fuzzy controlled system is improved by using the coarse and fine mode.

(3) The performance of the fuzzy PI controller is much superior to that of the conventional PI controller, in particular, robustness to the load disturbance.

Ⅵ. Appendix

The parameters of the SRM in this paper is as follows.

Rated Power : 200W, Voltage : DC 160V, Number of phase : 4, Maximum Speed : 5000 rpm, Number of stator poles : 8, Number of rotor poles : 6, Terminal resistance : 6.6Ω, Unsaturated aligned inductance : 119.12mH, Unsaturated unaligned inductance : 16.32mH, Rotor pole arc : 22.96°, Stator pole arc : 22.5°

Acknowledgments

The authors would like to appreciate the Korea Electric Power Corporation which supported fund for this project. No. 94-052. (1994.9 -1995.9)

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